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Application of Risk-based Analysis to Planning Reservoir and Levee Flood Damage Reduction Systems

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APPLICATION OF RISK-BASED ANALYSIS TO PLANNING RESERVOIR AND LEVEE FLOOD DAMAGE REDUCTION SYSTEMS [*]

Earl E. EIKER, PE
Chief, Hydraulics and Hydrology, HQUSACE

Darryl W. DAVIS, PE
Director, Hydrologic Engineering Center

David M. GOLDMAN, PE, Ph.D.
Senior Hydraulic Engineer, Hydrologic Engineering Center

U.S. Army Corps of Engineers

USA

1. INTRODUCTION

The U.S. Army Corps of Engineers (Corps) policy is to apply risk-based analysis in the formulation and evaluation of flood damage reduction projects. These projects include dams and reservoirs, levees and flood walls, diversions, channel modifications, bypass channels, and a variety of nonstructural measures. Most projects include more than one measure, particularly projects that include reservoirs. This policy is viewed as a significant step forward in improving the basis for Corps project development. The risk-based analysis approach explicitly incorporates uncertainty of key parameters and functions into project formulation, benefits, and performance analyses. Particular focus is the impact of the uncertainty in the discharge-probability, elevation-discharge, and elevation-damage functions that represent effects of the proposed protective works. Reservoir projects that reduce flood damage result in a downstream reduction in flood frequency. This paper briefly describes the risk-based analysis approach in contrast to historical project development study methods, and presents results of a recent risk-based analysis for the American River (near Sacramento, California, USA) project studies. Comments are offered on technical issues of methods and data, communication of risk-based analysis results with local officials and the public, and project design implications of the policy.

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[*] *Les applications du calcul du risque dans la formulation et l'évaluation des projets pour la réduction des dégâts dus aux inondations.*

2. CORPS HISTORICAL FLOOD DAMAGE REDUCTION STUDIES

The Corps historically used best estimates of the flood hazard and damage potential as reflected by discharge-frequency, water surface profiles (stage-flow rating), and stage-damage to formulate and evaluate project alternatives. The selected plan was the one that included the project components that reasonably maximized net flood damage reduction benefits subject to acceptable performance. Performance was characterized by the degree-of-protection concept, for example protection from the occurrence of the 100-year flood. Uncertainty in flood hazard and project performance was dealt with by application of professional judgement in selecting and sizing features, conducting sensitivity analysis, and in the case of levees and floodwall projects, the addition of freeboard to ensure performance for the design flood. Risk was considered by nominating several sizes and mixes of project features, each with acceptable performance, and selecting the preferred alternative.

Discharge frequency was developed by applying adopted U.S. Federal interagency guidelines [1] when gauged data were available, and rainfall-runoff models, such as HEC-1 [2] when watershed modeling was appropriate. Regulated frequency reflecting the flood control operation of reservoirs, was developed by routing of historical and hypothetical floods through the proposed reservoir under study. Uncertainty was considered by computing the expected probability estimate of the flow frequency curve [3]. This was done to correct the curve for bias resulting from a short length of record.

Stage-flow ratings were developed for most situations by water surface profile computations using, for example, HEC-2 [2]. When flow was complex or circumstances unusual, unsteady flow or two dimensional model computations were needed. Models were adjusted based on observed high-water-marks, available rating curves, and published guidelines. Uncertainty was sometimes considered by performing sensitivity analysis through evaluating the results of reasonable adjustments of model variables. The outcome of sensitivity analysis often resulted in adoption of model coefficients to ensure that computed water surface profiles were on the conservative side. Freeboard served to accommodate uncertainty in flood height resulting from uncertain or variable hydraulic (conveyance) factors for the adopted design flow.

The stage-damage curve reflected flood plain damage vulnerability and provided a summary statement of damage as a function of river stage or elevation. Damage was sensitive to a number of factors which were frequently recognized as important in understanding variation in damage from one structure to another but were rarely empirically verified. Uncertainty was sometimes considered by performing sensitivity analysis.

3. CORPS RISK-BASED ANALYSIS

Corps policy and technical guidance for flood damage reduction studies are described in USACE [4,5]. Corps policy now requires application of risk-based analysis in the formulation of flood damage reduction projects. The risk-based analysis approach is similar to Corps historical flood damage reduction study methods in that the basic data are the same; the significant departure is that

uncertainty is now explicitly quantified. Best estimates are made of discharge-frequency, water surface profiles (stage/flow rating), and stage-damage. Project alternatives are formulated and evaluated, and the selected project is that which reasonably maximizes expected net economic benefits subject to acceptable performance. The difference is that uncertainty in technical data is quantified and explicitly included in evaluating project flood damage reduction benefits and performance. Because of the risk-based approach, performance can now be stated in terms of expected annual exceedance and reliability of achieving stated performance goals. Also, adjustments to or additions of features to accommodate uncertainty, such as adding freeboard for levee/flood walls, are not included.

The method for development of discharge-probability and uncertainty relationships depends on data availability. For gauged locations and where an analytical fit is appropriate, the method defined by Bulletin 17B [1] is applied. Uncertainties for discrete probabilities are represented by the non-central *t* distribution. For ungauged locations, the discharge-probability function is adopted from applying a variety of approaches [1]. When justified, curve fit statistics for the adopted function are computed. An equivalent record length is assigned based on the analysis and judgements about the quality of information used in adopting the function. Regulated discharge-probability, elevation-probability, and other non-analytical probability functions require different methods. An approach using the theory of order statistics [5] is applied to develop the probability function and associated uncertainty for these situations.

Developing the regulated discharge probability, and its associated uncertainty, is the key task in reflecting the flood damage reduction performance of flood control reservoirs. Analysis must consider inflow magnitude and uncertainty, initial reservoir storage and associated variability, and operation rules and associated variations that occur during real-time operation, among other factors.

Elevation-discharge functions are developed for downstream flood plain index locations from measured data at gauges or from computed water surface profiles. For gauged data, uncertainty is calculated from the deviations of observations from the best fit rating function. Computed profiles are required for ungauged locations and for proposed project conditions that are modified from that of historic observations. Where sufficient historic data exists, profile uncertainty is estimated based on the quality of the computation model calibration to the historic data. Where data are scarce, or the hydraulics of flow complex, such as for high velocity flow, debris and ice jams, and flow bulked by entrained sediments, special analysis methods are needed. One approach is to perform sensitivity analysis of reasonable upper and lower bound profiles and use the results to estimate the standard deviation of the uncertainty in stage. Unless data indicate otherwise, the uncertainty distribution for flow-stage functions is taken to be Gaussian [5].

Elevation-damage functions are derived from inventory information about structures and other damageable property located in the flood plain. The functions are constructed at damage reach index locations where discharge-probability and elevation-discharge functions are also derived. Presently, separate uncertainty distributions for structure elevation, structure value, and

content values are specified and used in a Monte Carlo analysis to develop the aggregated structure elevation-damage function and associated uncertainty. The uncertainty is represented as a standard deviation of error at each elevation coordinate used for defining the aggregated function at the index location.

Computation of expected values of damage and performance without and with proposed reservoir and other flood damage reduction measures is performed using Monte Carlo Simulation. The Monte Carlo analysis samples the basic evaluation relationships and associated uncertainty to estimate expected values and associated uncertainty. Figure 1 illustrates the sampling of evaluation functions and computation of expected values.

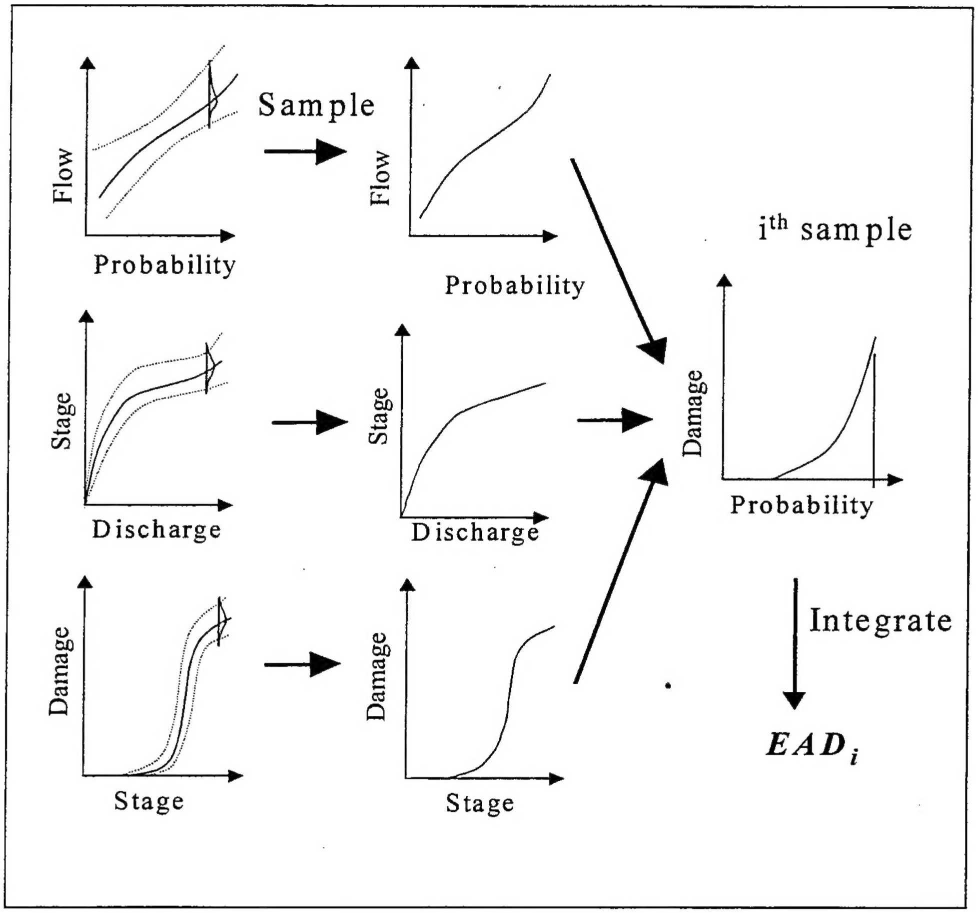

Fig. 1
Monte Carlo Sampling Strategy
La stratégie du échantillonnage de Monte Carlo

Project performance is obtained as a by product of the Monte Carlo simulation. The outcome is given in terms of expected flow and stage exceedance, and conditional non-exceedance probability (referred to in Corps documents as "reliability") of controlling a specified flood. Table 1 compares several key aspects of historical VS risk-based analysis concepts.

Table 1
Historical VS Risk-based

Topic	Historical Context	Risk-based Analysis Context
Flood Risk Data and Presentation	Flow, stage, exceedance probability – tabulations	RBA[1] explicitly quantifies/ applies uncertainty in data
Flood Plain Delineation	Median probability Q/S[1], Corps Ex. Prob. Q/S	Almost same; FEMA[1] median prob., Corps RBA - Ex. Stage
Flood Project Benefits	Stage, flow, damage – integration for EAD[1]	Explicit uncertainty, better EAD; EAD distribution
Flood Project Performance	Level-of-protection, capacity exceedance	Expected exceedance, conditional probability
Flood Project Selection	Acceptable alternatives, net expected benefits	Same, improved estimate of net expected benefits

[1]RBA - Risk-based analysis; Q/S - flow/stage; EAD - Expected annual damage; FEMA – Federal Emergency Management Agency.

4. AMERICAN RIVER PROJECT, CALIFORNIA, USA EXAMPLE

4.1 INTRODUCTION

The City of Sacramento is located at the confluence of the Sacramento and American Rivers in central California. Throughout history, the city has been vulnerable to floods from both the Sacramento and American Rivers. The Sacramento River and upstream tributaries are controlled by a series of dams and other protection works. The flood threat from the American River remains serious. The topography of the American River, which drains an area of about 5,440 km^2, varies from flat valley areas, to rolling foothills, to steep mountainous terrain.

Sacramento is protected by a complex system of dams, diversions and levees. Folsom Dam, located on the American River, about 47 kilometers upstream from Sacramento, is a key feature in the flood control system protecting the city. Folsom Reservoir has a capacity of 1,200 x 10^6 m^3, which includes a minimum of 490 x 10^6 m^3 of storage seasonably dedicated to flood control. Currently, Folsom Dam is operated to provide additional flood space in years with high forecasted runoff under an agreement between the U.S. Bureau of Reclamation (USBR), which owns and operates Folsom, and the Sacramento Area Flood Control Agency (SAFCA). Figure 2 shows the existing reservoir, levee, and bypass flood control system in the Sacramento area.

Releases from Folsom Reservoir flow through a system of levees in Sacramento. The "objective release," or flow that can be safely conveyed by the

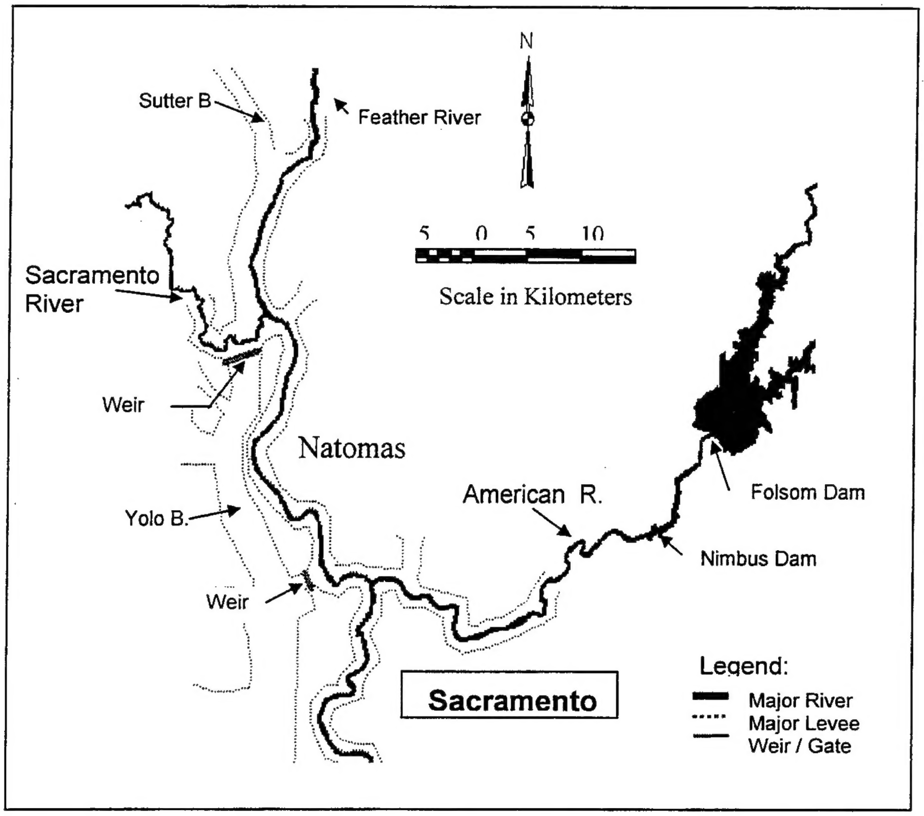

Fig. 2
Sacramento Area Flood Damage Reduction System
Le système de maîtrise des crue les environs du Sacramento

leveed downstream channel, is 3,256 m^3/s. Studies have shown that the levees along the American River downstream from Folsom are likely to fail at several locations when sustained flows are between 3,680 and 4,530 m^3/s. The risk of levee failure during the occurrence of a 100-year flood ($Q = 4,110$ m^3/s) is about 60 percent with the present operation of Folsom Dam, as determined using risk-based analysis.

Levee failure along the American River could result in flooding of more than 40,500 ha, affecting more than 400,000 residents in the flood plain. Damages would range from $7 billion US from flooding from a 100-year flood to more than $16 billion US for a 400-year flood. Such flooding would result in the loss of many lives due to drowning from rapid inundation of the flood plain, and other impacts on public health and safety after the floodwaters recede. Damage from toxic and hazardous waste contamination would be extensive, and environmental resources in the flood plain would be lost. Disruptions to commercial activities and transportation would be catastrophic.

4.2 THE FLOOD PROBLEM

In February 1986, the "flood of record" in the American River basin severely tested the flood control system. Releases from Folsom Dam reached 3,795 m^3/s

(or 540 m^3/s greater than "safe" flow capacity) for a few days, placing the entire flood control system in jeopardy. Significant flood damage occurred in unprotected areas, and it is estimated that if the high releases had continued, major levee failures would have resulted with significant loss of life and billions of dollars in damages.

As a result of the 1986 flood, a flood plain study was conducted in 1988 for the Federal Emergency Management Agency (FEMA). This study concluded that much of the Sacramento urban area was within the 100-year flood plain. The existing flood control system was estimated to be capable of providing only a 63-year level of flood protection, well below the 100 year level required under the National Flood Insurance Program administered by FEMA.

4.3 PRIOR STUDIES AND EVALUATIONS

As a result of the flood threat, in July of 1986 the State of California and the Corps initiated a feasibility study of the American River Watershed. In December 1991, the Corps published the Feasibility Report and Environmental Impact Statement describing the results of this study. It identified a selected plan to resolve the problems. Public comments on an earlier draft of the report and the selected plan were incorporated into a final report that was submitted to Congress for construction authorization. The report [6] contained a recommendation to construct levee and related improvements in the Natomas area of Sacramento and a flood detention dam on the North Fork American River, near Auburn, CA. In 1992, Congress authorized construction of the Natomas portion of the recommended plan, which has been constructed by SAFCA, and requested additional information on the flood detention dam and other feasible flood protection measures for the main stem of the American River because of environmental concerns with the detention dam portion of the plan.

In response to the 1992 legislation, the Corps prepared a new report as a supplement to the feasibility report. This report reassessed the risk to the Sacramento area from flooding by the American River and evaluated a range of flood protection measures to reduce the risk. It described several additional alternatives, including combinations of the individual measures. This report has a main report, which focuses on the flood protection alternatives, and a final supplemental environmental impact statement. Alternatives were formulated to substantially increase Sacramento's flood protection. At that time, increasing the seasonal flood space and surcharge storage in Folsom Reservoir together with lowering the spillway and enlarging the regulating outlets could increase flood protection to nearly the 200-year level. These changes plus levee work downstream to accommodate larger flood releases from Folsom might increase protection to about a 300-year level . Higher levels of protection were possible only with additional flood storage upstream from Folsom Reservoir. The alternatives were presented in a November 1994 report [7]. Again, the Detention Dam Plan was recommended.

Because of continued controversy related to the Detention Dam Plan, additional studies are on-going. Studies subsequent to the November 1994 report include application of risk-based analysis, since Corps policy addressing this topic was initially issued in 1993. The policy was updated in 1996 [4].

4.4 AMERICAN RIVER PROJECT ALTERNATIVES STUDIED

The goal of the continuing American River Project studies is to develop and implement a project that significantly increases flood protection for Sacramento. The local sponsor, SAFCA, indicates that a flood control alternative implemented in the Sacramento area should provide at least a 200-year level of protection. Seventeen individual measures were identified as possible configurations for project alternatives. These measures were arranged to compile an array of eight possible flood control alternatives (See Table 2). The alternatives fall into three basic categories: a flood detention dam on the North Fork of the American River just upstream of Folsom Dam; operational and structural modification to Folsom Dam; and larger flood control releases from Folsom Dam requiring modification of Folsom Dam and the downstream flood control system. The candidate plans for these three categories are referred to as the Detention Dam Plan, the Folsom Modification Plan, and the Folsom Stepped Release Plan.

4.5 RISK-BASED ANALYSIS

Risk-based analysis (RBA) procedures were used to evaluate the performance and flood damage reduction benefits of each alternative. Nine locations were selected as indexes to characterize the hydrologic and flood damage effects of without and with project alternatives. These index locations

Table 2 - Summary of Initial Alternatives

Alternatives	Primary Alternative Features
Minimum Impact [1] Folsom Modification Plan	Increase flood control space, surcharge space, modify Folsom outlets, minor change to objective release and downstream channel capacity (3,260.m^3/s)
Minimum Objective Release	Increase flood control space, surcharge space, modify Folsom outlets, minor change to objective release and downstream channel capacity (3,680 m^3/s).
Moderate Objective Release	Increase flood control space, surcharge space, modify Folsom outlets, moderate change to objective release and downstream channel capacity (4,110 m^3/s).
Maximum Objective Release	Increase flood control space, surcharge space, modify Folsom outlets, major change to objective release and downstream channel capacity (5,100 m^3/s).
Stepped Release [1]	Increase surcharge control space, surcharge space, modify Folsom outlets, major change to objective release and downstream channel capacity (4.11-5,100 m^3/s).
200-Year Storage	Construct a 470 x 10^6 m^3 flood detention dam upstream from Folsom Reservoir.
Equivalent Storage	Construct a 670 x 10^6 m^3 detention dam upstream from Folsom Reservoir.
Detention Dam Plan [1]	Construct a 1,100 x 10^6 m^3 flood detention dam upstream from Folsom Reservoir.

[1] Final candidate plans

are located upstream and downstream of Sacramento on the Sacramento River, within the flood bypass channels, and on the American River below Folsom Dam. Hydrologic performance was evaluated at all nine locations, and flood damage reduction benefit analysis was performed at two of these index locations. The index location below Folsom Dam is used herein to illustrate RBA analysis needs and results. The following paragraphs discuss data preparation and RBA analysis. The information is adapted from [8].

4.5.1 HYDROLOGIC ANALYSIS

The American River system is regulated via several small reservoirs in the upstream watershed and by Folsom Dam and Reservoir on the mainstem. Reservoir routing to determine the inflow/outflow characteristics of the storage components was performed using volume balance analysis incorporating spillway and outlet ratings and operational criteria. The HEC-2 steady flow model [2] was used to develop stage-discharge data, and the UNET unsteady flow model [2] model was used to develop stage-frequency data and to route outflow hydrographs throughout the system. Figure 3 presents a schematic of the hydrologic analysis, including the error distributions for each function.

In 1961, a statistical analysis was performed to establish the flood frequency in the American River downstream from Folsom Dam. However, because the 1986 flood and five of the ten largest flows in the basin for the 82 years of record have occurred since 1961, and seven of the 10 largest events have occurred since 1951, a new flow-frequency analysis was conducted in 1988. A subsequent analysis was performed to include the last eight years of record through 1997. The re-analysis included establishing the adjusted unregulated flow and removing the routing effects of the upstream storage including Folsom Reservoir. The guidelines set out in Bulletin 17B [1] were followed in the analysis. Because of the controversy over project proposals, the development of the inflow frequency curve was reviewed by a committee of national experts [9]. The uncertainty in the unregulated Folsom Reservoir inflow discharge-frequency function is based on the period-of-record of 90 years.

The lower American River is a highly regulated system with Folsom and Nimbus Dams located immediately upstream. Nimbus Dam is a power re-regulating dam with no discernable regulating effect on flood flows. Flows and stages in the river are controlled by releases from Folsom Dam. Consequently, the performance of project alternatives and flood damage reduction benefit computation via simulation must sample Folsom outflow, use stage-discharge functions that represent system performance with the levees in place, and employ uncertainty functions representative of these conditions. An inflow-outflow function was developed by repeatedly computing outflow peaks for given inflow peaks. Reservoir routing to determine the inflow-outflow characteristics of the storage components was performed using a volume balance analysis incorporating spillway and outlet ratings and operational criteria. Table 3 summarizes the operational criteria used to perform the base routing and to develop the base and alternative inflow-outflow functions. Figure 4 presents an example of the structure of such a function and is presented in the figure as the most likely case.

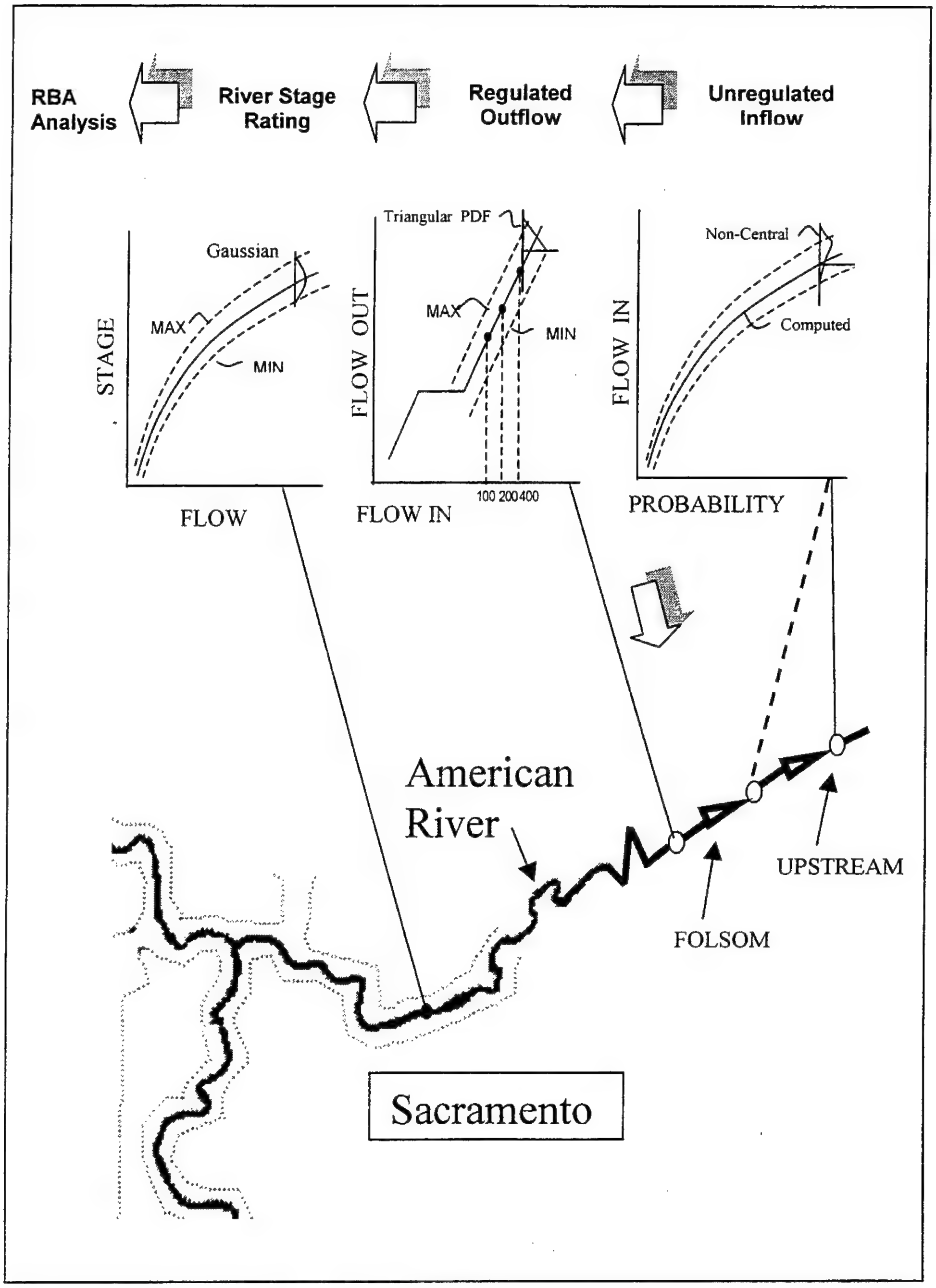

Fig. 3
Lower American River Hydrologic Uncertainty Analysis
L'analyse de l'incertitude de la hydrologie du fleuve d'American

There are uncertainties in the operation of Folsom and the performance of the proposed upstream detention dam facility. Itemizing all possible parameters that may impact the outflow was the first step in establishing an uncertainty distribution about the inflow-outflow function. The list included items such as:

Table 3
Operation Criteria for Without Alternatives Reservoir Routing

CURRENT OPERATION ASSUMPTIONS
Multiple Floods (Two 4-day Sequences)
No Initial Encroachment
Initial Release of 225 m^3/s (Maximum Power)
Initial Flood Release Delay of 10 Hours (Applied to Second Flood Sequence if Flood Reservation was Evacuated)
4 Hour Response Time Matching Outflow to Inflow
Rate of Change of Release Increase – 142 $m^3/s/hr$ to 710 m^3/s - 425 m^3/s /hr above 710 m^3/s Decrease – 142 m^3/s /hr
Folsom Dam Release – Existing Full Capacity of Main Spillway in Combination with River Outlets (60% Gate Opening) Power Release of 225 m^3/s (Full Capacity)
Surcharge as Prescribed by Emergency Spillway Release Diagram
Routing with Credit for Upstream Space - Reduce Folsom Unregulated Inflow by 12%

variances in spillway gate operations; hydropower penstock operations; river outlet cavitation requiring modification to releases; insufficient personnel to make matching changes at Nimbus and Folsom Dams; political pressure to change operations; inaccurate inflow data; flood event sequences varying from the expected; and the amount of space in Folsom Reservoir. For most of these items it was difficult to quantify the resulting uncertainty on Folsom operation. However, it was determined that sets of conditions could be identified to describe the most likely "best" and most likely "worst" set of conditions that could occur to set the bounds on the operation. These combinations and subsequent sensitivity routings were cast into a triangular probability distribution function (PDF) of uncertainty about the inflow-outflow function. These triangular distributions were typically asymmetric. Sensitivity runs were made to determine how many factors should be combined to capture approximately 95 percent of the uncertainty.

Table 4 shows the criteria used to set the operational bounds on the inflow-outflow curve for an example alternative that included a detention dam at Auburn

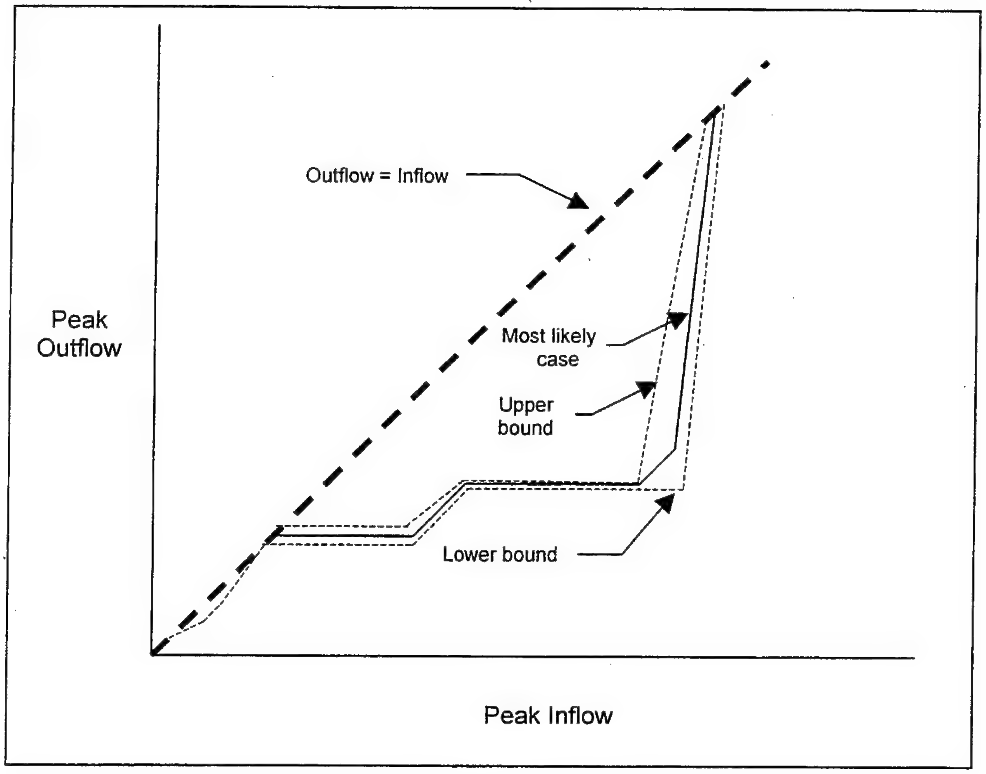

Figure 4
Example Regulated Flow – Uncertainty Diagram
L'exemple: La figure de l'incertitude pour débit contrôlés

Table 4
Folsom Dam Operation Uncertainty
Existing Re-operated Folsom Dam and Upstream Detention Dam

	Operations Conditions		
Factor	Base	Maximum	Minimum
Extra Space in Folsom Lake	0	0	$123 \times 10^6 m^3$
Flood Sequences	2	2	1
Upstream Reservoir Space	0	0	$185 \times 10^6 m^3$
Outlet Works Operation	60%	0%	60%
Spillway Efficiency	Free Flow	1 m Surcharge	Free Flow
Initial Delay in Releases	10 hours	24 hours	0

and re-operation of Folsom Reservoir. For each alternative, inflow-outflow curves with uncertainty were developed as input to the risk-based analysis. This outflow uncertainty distribution is used in the EAD computations. The sampled discharge with uncertainty is treated as Folsom inflow. The outflow with error is found by sampling the triangular distribution defined about the most-likely outflow. There is no uncertainty for the flat part of the curve (no objective release uncertainty).

4.5.1.2 Stage-Discharge Functions

An HEC-2 model of the American River from Nimbus Dam to its confluence with the Sacramento River was available from previous studies. The model was calibrated using high water marks recorded during the February 1986 flood. The starting water surface elevations for the study were developed using a model of the American and Sacramento Rivers confluence area assuming no upstream levee failures on either the American or the Sacramento River system.

Uncertainty in stage was determined through a sensitivity analysis for defining the upper and lower limits for the one-percent chance flood. The sensitivity analysis included variations in: the Manning's roughness coefficients; sediment accumulation; bridge blockage; and uncertainty in: cross-section definition; starting water surface elevation; cross section geometry; and scour. Water surface profiles were computed for the cumulative maximum sensitivity condition, and the cumulative minimum sensitivity condition. Computed profiles ranged from .3 m to .6 m higher at the downstream and upstream ends respectively, and to about .45 m lower for the reach. Given this range, a standard deviation for the uncertainty in stage was selected at .3 m.

4.5.2 GEOTECHNICAL ANALYSIS

An additional element considered in this RBA is the geotechnical performance of the existing levees. A method [10] incorporating probable failure and non-failure elevations determined from geotechnical analysis was used. The Probable Non-failure Point (PNP) is defined as the elevation below which it is highly likely that the levee would not fail. The Probable Failure Point (PFP) is defined as that stage above which it is highly likely that the levee would fail. Uncertainty in geotechnical performance of the existing levees is included in the Monte Carlo analysis by sampling the PNP-PFP function during simulation.

There are approximately 35 km of levees protecting the land north and south of the American River. For the Lower American River project reach, the PNP/PFP values were determined primarily by using slope stability criteria developed in a 1988 report and data on levee performance during the 1986 flood. An evaluation of land-side slope instability was conducted at each cross section. It was determined that for a levee section to be considered stable, three criteria should be met. The criteria for a stable levee are: 1) a minimum of .9 m of freeboard; 2) an estimated steady seepage water exit height above the land-side levee toe of no more than 0.2 m; and 3) a hydraulic head difference between flood stage and the adjacent land-side levee toe of no more than 1.8 m. With consideration of 1986 levee performance, the PNP values along the lower American River were determined at least equal to the 1986 flood level, which is equivalent to a flow of approximately 3,700 m^3/s.

4.5.3 ECONOMIC ANALYSIS

The flood damage reduction benefit analysis is based on October 1995 price levels, 7 5/8 percent interest rate, a 100 year project life, and future growth conditions from 1995 to 2008. Damage categories included residential,

commercial, industrial, public, agricultural, emergency costs, and auto. The structures located within the flood plain were inventoried and aggregated into elevation damage functions – one for the Natomas area, and one the greater Sacramento area. The Sacramento index location was composed of five sub-reaches. Because the analysis was performed during the transition from historical Corps flood damage reduction methods to the risk-based analysis policy, uncertainty was not considered for the flood damage functions.

After configuring the initial seventeen potential measures into the eight initial alternatives in Table 2, risk-based analysis was performed by applying the Monte Carlo simulation analysis illustrated in Figure 1. The analysis proceeded in two steps. First, for alternatives that included increased releases from Folsom Reservoir, hydraulic impacts to the downstream system were evaluated. As compared to the no-action system performance matrix, if there was a decrease in the levee reliability or increase in expected annual exceedance at any given index point, hydraulic mitigation features were included into that alternative and the cost adjusted. Additionally, once a full alternative was structured and the associated costs were calculated, the EAD and net benefits were determined to narrow the array of alternatives. The final array of alternatives was reduced to the no-action plan and the three plans shown in Table 5. A final incremental analysis was performed on these plans cycling through the measures that made up that alternative to ascertain which features were the most cost effective.

Table 5 - Summary of American River Risk-Based Analysis

	Alternative (1)			
	No-Action Plan	Folsom Modif-ication Plan	Folsom Stepped Release Plan	Detention Dam Plan
Probability of Flooding in any one year (2)	1 in 67	1 in 153	1 in 192	1 in 500
Probability of Passing (2)				
100-yr Flood (%)	31	83	90	99+
200-yr Flood (%)	5	43	48	94
400-yr Flood (%)	1	12	22	73
Benefit Summary ($ Million US)				
First Cost ($ Million)	-	370 – 430	505 – 650	960 – 1000
Annual Cost	-	50+-	75+-	95 +-
Expected Annual Benefit	-	125+-	130+-	200 +-
Expected Annual Net Benefit	-	75+-	60+-	110+-

(1) Alternative feature description, costs and benefits are based on 1998 data.
(2) Performance parameters for each alternative are computed based on 1999 hydrologic parameters.

4.6 RESULTS

Table 5 summarizes the results of the RBA studies. The analysis revealed a substantial difference in the flood reduction benefits afforded by increased upstream storage as opposed to increased Folsom outflow releases and modification to the downstream system. The annual net benefits for the detention dam and the increased downstream system was $109 million US and $77 million US, respectively. The probability of failure in any one year is less than 1 in 500 for the detention dam and 1 in 192 for the stepped release plan.

4.7 CURRENT STATUS OF AMERICAN RIVER STUDIES

There has been little real progress in implementing additional flood damage reduction measures for the American River since the occurrence of the 1986 flood. This has been the result of strong environmental opposition to the construction of any additional upstream storage reservoir for flood control. Even though the upstream reservoir proposals to date have been for single-purpose flood control only projects, the concern among environmental groups has been that any structure built to provide additional flood control storage would soon be converted to multi-purpose use.

In an attempt to further analyze alternatives that potentially could break this impasse, the Corps undertook yet another evaluation, in 1999, of four plans that essentially were modifications of previously studied plans. Results of this evaluation were presented in [11]. The paper was prepared for the purpose of providing decision makers with more detailed information on four alternatives, under consideration for authorization by the U.S. Congress, to increase flood protection for the City of Sacramento.

Plan 1 entails the enlarging of existing outlets and the addition of five new outlets in Folsom Dam to increase release capability and provide more efficient utilization of existing flood storage. Plan 2 provides for the modification of Folsom Dam as in Plan 1, and increasing maximum objective releases from Folsom from 3,256 m^{3}/s to 5,090 m^3/s. Plan 2 also requires raising and strengthening 80 km of downstream levees along with widening the Yolo Bypass by 305 m to carry the increased releases from Folsom Dam. Plan 3 entails the Folsom modifications in Plan 1, plus spillway modifications and a 2.0 m raise of Folsom Dam to increase the amount of controlled flood storage. Plan 4 entails the Folsom modifications in Plan 1 in addition to the construction of a small 220 x 10^6 m^3 flood detention reservoir upstream of the Folsom Reservoir.

Two other important elements in final plan selection, residual risk, in terms of both damages and hazard to human life that would result if the design capacity of a given plan were exceeded, and environmental impacts and enhancements were discussed only superficially in the paper. In the absence of detailed residual risk (see section 7.) and environmental analyses, Plan 4 (upstream storage) once again is clearly the superior plan based on economics and reduction in overall exposure to risk. It provides the greatest net annual benefits ($53.2 million US) for an initial cost of $413.5 million US. It has a BCR of 2.4, the minimum annual chance of flooding (1 in 200 in any year) and the maximum reduction in flood risk (55%) among the four plans evaluated in this study.

Decisions made in the past to not pursue authorization of upstream storage for flood control at Auburn were based largely on environmental impacts related to a multi-purpose reservoir. However, the water control plan for an upstream single purpose flood detention dam (e.g. Plan 4) could be developed to store water only after Folsom capabilities were exhausted. Thus, the probability of storing large amounts of water for significant periods of time at Auburn would be roughly the same order of magnitude as the probability of the levees being overtopped if an alternative without upstream storage is implemented. In other words, the choice could be characterized as being between storing water in the American River Canyon and catastrophic flooding in Sacramento.

5. RISK-BASED ANALYSIS AND AMERICAN RIVER DECISIONS

5.1 NON-FEDERAL PERSPECTIVE

The representative of the sponsoring local government agency (SAFCA) presented a paper [8] that commented on public perceptions of risk, risk communications, and the contribution of RBA to better understanding of the performance of project proposals. In the paper, it was noted that . .

> "Yet, in the minds of the general public, this risk is not real. Yes there are areas which have flooded, but generally they are the same areas which always flood. The bulk of the populace sits behind the levees oblivious to the potential risk. Over the past six years working in Sacramento, I have been approached by literally dozens of people who confidently proclaim they have never [been] flooded since living in their houses and therefore do not believe they are at risk of flooding in the future."

It was further noted that even agency staff and elected officials had trouble with understanding the notions of risk associated with flooding. In the end, the agency has chosen to describe flood risk in its communications in terms of risk of flooding over a 30 year period – typical mortgage life of a private home - (rather than annual risk). The result of the risk-based analysis that is used to compute the risk is the expected exceedance (uncertainty-weighted exceedance) rather than the historical annual exceedance. The local agency thus seemed to understand and appreciate the more accurate estimate of risk produced by RBA. On the other hand, the conditional non-exceedance probability performance characterization has not found use by SAFCA.

5.2 RBA UNIQUE CONTRIBUTION

An interesting instance where the conditional non-exceedance probability information helped the Corps and other agencies better understand the performance of a proposal involved the stepped release plan. This plan was carefully crafted by a local consultant to shape the releases such that the operation precisely controlled the 200-year event (not greater events) and thus would meet the local agency's performance goal. In the historical context, the project would be characterized as providing the 200-year level of flood protection and would permit certification against the FEMA standard 100-year flood. Because this plan released water at a rate that that would be almost exactly at the top of the levees, the 'assured' protection characterization in this plan is questionable. In this plan, there is little margin for error and thus, uncertainty is an important factor. The RBA results demonstrated the mis-characterization of the performance of the plan by producing a more accurate expected exceedance estimate (1 in 169), and demonstrating via conditional non-exceedance probability that the assurance of passing the 100-year FEMA flood (87%) was marginal. Without RBA, the risky nature of the alternative could have been argued, but its shortcomings would not have been quantified.

5.3 IMPROPER USE OF RBA RESULTS

There was one particularly notable instance of the RBA reliability results being used by a Congressman to mislead the public [12]. In a committee hearing, a question was asked by the Congressman of a Corps official in such a way that resulted in his characterizing a particular alternative as "only having a 60% chance of passing the 200 year flood". The Congressman then sent out flyers to the populace characterizing the performance of this particular alternative as analogous to asking someone to board an airplane that had a 40% chance of crashing. The context and information were obviously misconstrued to the detriment of public discourse on the merits of the alternatives and the true nature of the flood risk for Sacramento.

6. COMMUNICATING RBA PERFORMANCE RESULTS

Explaining the Corps RBA procedure for formulation of flood damage reduction projects has proven to be quite difficult. This is particularly true of the statistics that are used to describe the expected performance of alternative plans. In a traditional flood damage reduction study, 'best estimates' of the various engineering parameters are used to formulate the size and scope of the project. The uncertainties are treated in a surrogate way by adding freeboard or making similar accommodations. Project performance is typically described as a unique 'level of protection' (LOP) that is expressed as the average return period in years (i.e., frequency of occurrence) of the largest flood that can be accommodated by the project, with a high degree of assurance. The relative performance among the alternatives was inferred by comparing the LOP associated with each plan.

The RBA method considers the same engineering and operational parameters as in the traditional analysis, but explicitly accounts for the inherent uncertainties in these parameters as an integral part of the analysis. Project performance is measured in terms of how a given size and/or type plan will function when exposed to the full range of floods that could occur (expected annual exceedance probability) and to a specific frequency flood (conditional non-exceedance probability). Performance of the alternative plans can then be compared based on either the full range of floods or a specific frequency flood.

In a RBA, the "expected annual exceedance probability" is the probability that a project's design capacity will be exceeded in any year. It is a term that has been suggested as being analogous to the LOP developed in the traditional analysis. This is not the case since LOP is defined as the recurrence interval of the largest flood that can be contained by the plan under study with a high level of assurance, while the expected annual exceedance probability reflects the chance of the plan design being exceeded in a given year by any flood that might occur. The "conditional non-exceedance probability" (CNP), is a companion indicator of project performance that is a direct measure of how a plan will perform when subjected to a specific frequency flood. It answers the question; "What is the chance that a specific frequency flood, e.g., the 100 year or 1% chance flood, can be contained by a specific flood damage reduction project?" The answer, stated as a percentage chance, embodies the knowledge of the stated flood and accounts for engineering and operational uncertainties. This is a key concept and is very useful in comparing performance of alternative plans.

Non-Federal project sponsors, and others, continue to depend on the use of LOP to communicate expected project performance and to serve as a means to compare the expected performance of alternative plans. In an attempt to accommodate this desire, documents recently prepared by several Corps district offices incorrectly reported the reciprocal of the expected annual exceedance probability as the LOP provided by various project alternatives. Based on the previously noted definition of LOP for traditional flood damage reduction studies, it is clearly improper to ascribe the term LOP to the reciprocal of the expected annual exceedance probability derived using RBA methods. Improper use and interpretation of the RBA performance statistics points to the need for a consistent "operational definition" of LOP, based on outputs from the RBA, which can be used to describe performance of alternative plans. To resolve this issue, the following operational definition of LOP is being considered to describe the expected project performance of alternative plans analyzed using RBA methods:

> "Level of protection is expressed as the average return period in years of the largest flood that can be accommodated by the plan under study, with a conditional non-exceedance probability of 90 percent".

This operational definition of LOP allows communication with agencies and individuals outside the Corps in familiar terms (i.e. a unique LOP for each alternative studied) and is compatible with Corps policy on minimum project performance requirements (i.e. 90 % CNP) for Corps certification of levees under the National Flood Insurance Program administered by FEMA.

7. DESIGN IMPLICATIONS

A Risk-based Analysis is only one component of a much larger process in a flood damage reduction study. While RBA provides a wealth of information that was not previously available, it is not a substitute for good engineering practice, nor is it intended to be. The RBA is used to formulate the type and size of the optimal structural (or non-structural) plan that will meet the study objectives. Corps policy requires that this plan be identified in every flood damage reduction study it conducts. This plan, referred to as the National Economic Development (NED) plan, is the one that maximizes the net economic benefits of all the alternatives evaluated. It may or may not be the recommended plan based on additional considerations.

The first step in a flood damage reduction study is to conduct the RBA. A residual risk analysis for the NED Plan is next performed to determine the consequences of a capacity exceedance. We know that for a flood damage reduction project, the question is not "if" the capacity will be exceeded, but what are the impacts "when" that capacity is exceeded, in terms of damage and the threat to human life. If the residual risk is unacceptable, and a design to reduce that risk cannot be developed, other alternatives must be analyzed. Either additional features must be incorporated into the plan, to assure sufficient time for evacuation, or a different type of project, with less residual risk, should be selected to reduce the threat to life and property.

The design must also include measures to minimize the adverse impacts of a capacity exceedance. For levee projects (or combined levee and reservoir

projects), the final levee grade is usually set so that initial overtopping will occur at the least hazardous location along the line-of-protection, usually at the downstream end of the levee. This assures that filling of the protected area will take place at a gradual rate and velocities in the protected area will be minimized, thus providing maximum time to institute emergency evacuation measures. For reservoirs, the Water Control Plan is developed so that as the point of downstream capacity exceedance is approached, the reservoir is operated to effect a gradual increase in outflow. This provides time to initiate emergency measures downstream. Upstream diversions are also configured to allow a gradual increase in flow during a design exceedance.

The American River is an illustrative example of where these considerations are critical. The main areas of protection for the American River project, Natomas and downtown Sacramento, are configured such that design of standard overtopping management features is not possible. If the American River levees are overtopped and/or breached, the protected areas will fill rapidly to depths in excess of 3 m. This will severely limit egress and will likely result in catastrophic loss of life, unless another way to manage the capacity exceedance is included in the selected plan. Folsom reservoir does not presently have sufficient capacity nor operational flexibility to allow for management of such a capacity exceedance. This is because Folsom is presently operated to maximize the amount of protection provided by the project, with little consideration of the consequences of a system capacity exceedance. Under this operating condition, the only way to provide assurance of egress from the protected area and enough time for evacuation is to provide additional upstream storage. With additional storage, a Water Control Plan could be developed for Folsom that would assure a gradual increase in outflow as the capacity of the of the system is approached.

Design of a flood damage reduction project places a special responsibility on the design engineer because of the potentially catastrophic consequences of a capacity exceedance. Of the types of structural projects usually considered in a flood damage reduction study, a levee is by far the most dangerous due to the severe consequences that may result from overtopping. Reservoirs, channels and upstream diversions are generally better choices than levees. They provide some measure of protection even after their design capacity is exceeded, and, they are better suited to minimize the adverse impacts of a capacity exceedance because they can be designed and/or operated to effect a gradual increase in flows and inundation in the protected areas.

8. CONCLUSIONS

The U.S. Army Corps of Engineers is committed to the application of risk-based analysis in the formulation of flood damage reduction projects. The advantage of this new analysis method is in the explicit incorporation of the uncertainty associated with many engineering and economic parameters directly into the analysis, thus minimizing the need to rely heavily on engineering judgement and the use of surrogates to account for uncertainty. The analysis provides a level of insight into expected project performance that is not available when traditional methods of analysis are used. While some problems remain, particularly with respect to communication of results to non-technical audiences, the overall success of risk-based analysis has been proven by numerous

applications such as the American River presented in this paper. As additional experience is gained in using risk-based analysis, engineers will become more comfortable and creative in the application of this powerful new procedure.

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SUMMARY

This paper describes the philosophy and application of risk-based analysis by the U.S. Army Corps of Engineers in the formulation and evaluation of flood damage reduction projects. Types of projects evaluated using risk-based analysis include dams and reservoirs, levees and flood walls, diversions, channel modifications, bypass channels, non-structural measures and combinations thereof. The application of risk-based analysis principles is considered a significant step forward in improving the basis for flood damage reduction project formulation.

The risk-based analysis approach explicitly incorporates the uncertainty inherent in key engineering and economic parameters and functions into project formulation, estimation of benefits, and performance analyses. Monte Carlo simulation is used to assess the impact of the uncertainty on the discharge-probability, elevation-discharge, and elevation-damage functions that represent existing conditions and the flood damage reduction effects of proposed protective works. The risk-based analysis provides important information on the expected project performance, not available with traditional methods of evaluation, that is of great value to decision makers in comparing alternatives.

The paper briefly summarizes the risk-based analysis approach, contrasts it to traditional project development study methods, and presents the results of a recent application of the methodology in studies conducted for the American River, near Sacramento, California, USA. Alternative project measures for the American River that were evaluated included new upstream storage, modification of an existing dam and present storage allocations and operation rules, raising and strengthening downstream levees, and various combinations of these alternative measures. Topics addressed in the paper include technical issues related to methods and data, communication of risk-based analysis results to local officials and the public, and project design implications.

RÉSUMÉ

Ce rapport décrit la philosophie et l'application du calcul du risque par le Corps des Ingénieurs de l'Armée Américaine dans la formulation et l'évaluation des projets pour la réduction des dégâts. Les types des projets utilisant calcul du risque comprennent les barrages et les retenues, les levées et les murs contre-crues contre-courbes, les dérivations, les modifications aux chenaux, les chenaux de contournement, les mesures non-maquette, et les combinaisons de cela. L'application des principes du calcul du risque est considérée comme un pas en avant pour améliorer la base de la formulation du projet pour réduire les dégâts dus aux inondations.

L'approche calcul du risque incorpore explicitement l'incertitude inhérente aux principaux paramètres et fonctions économiques et l'engineering dans la formulation du projet, dans l'estimation des bénéfices et dans les analyses des résultats. La méthode de Monte Carlo détermine l'impact de l'incertitude sur les fonctions qui représentent les conditions actuelles, et les effets de la réduction des dégâts produits par les constructions protectrices proposées. Ces fonctions

comprennent la détermination de la probabilité des débits, l'élévation des débits, et les dégats-élévation. Avec calcul du risque les décideurs ont les informations importantes sur les résultats anticipés du projet qui ne sont pas disponibles avec les méthodes traditionnelles d'évaluation pour comparer les alternatives.

Ce rapport résume l'approche calcul du risque et la contraste avec les méthodes traditionnelles pour l'étude d'un projet. Il présente les résultats d'une application récente de cette méthodologie faits au cours des études du American River près de Sacramento, Californie, EU. Incluses parmi les mesures alternatives étudiées sont de nouvelles retenues en amont, la modification d'un barrage actuel, le changement de ses allocations de retenue et de ses règlements d'opération. On a considéré l'élévation et la fortification des levées en aval et des combinaisons divers de ces mesures alternatives. Les sujets adressés dans ce rapport comprennent les questions techniques relatives aux méthodes et aux données, la communication des résultats du calcul du risque aux autorités civiles et au public, et les implication du dessein du projet.

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Earl Eiker, Darryl W. Davis and David M. Goldman

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609 Second Street
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13. ABSTRACT *(Maximum 200 words)*

The U.S. Army Corps of Engineers (Corps) policy is to apply risk-based analysis in the formulation and evaluation of flood damage reduction projects. These projects include dams and reservoirs, levees and flood walls, diversions, channel modifications, bypass channels, and a variety of nonstructural measures. Most projects include more than one measure, particularly projects that include reservoirs. This policy is viewed as a significant step forward in improving the basis for Corps project development. The risk-based analysis approach explicitly incorporates uncertainty of key parameters and functions into project formulation, benefits, and performance analyses. Particular focus is the impact of the uncertainty in the discharge-probability, elevation-discharge, and elevation-damage functions that represent effects of the proposed protective works. Reservoir projects that reduce flood damage result in a downstream reduction in flood frequency. This paper briefly describes the risk-based analysis approach in contrast to historical project development study methods, and presents results of a recent risk-based analysis for the American River (near Sacramento, California, USA) project studies. Comments are offered on technical issues of methods and data, communication of risk-based analysis results with local officials and the public, and project design implications of the policy.

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TP-154 Modeling Water-Resource Systems for Water Quality Management
TP-155 Runoff Simulation Using Radar Rainfall Data
TP-156 Status of HEC Next Generation Software Developmment
TP-157 Unsteady Flow Model for Forecasting Missouri and Mississippi Rivers
TP-158 Corps Water Management System (CWSM)
TP-159 Some History and Hydrology of the Panama Canal
TP-160 Application of Risk-based Analysis to Planning Reservoir and Levee Flood Damage Reduction Systems